CA816 Georgia Institute of Technology
Office of Contract Administration 06-NOV-1997 14:49
OCA PAD AMENDMENT - PROJECT HEADER INFORMATION

Document Header Id #: 35941 ACTIVE
Project #: E-16-X68 Cost share #: Rev #: 3
Center #: 10/24-6-R8470-0A0 Center shr #:
OCA file #: Project type: RES

Contract #: F49620-95-1-0241 Mod #: P-1 Award type: GRANT
Prime #: Contract entity: GTRC
Contract type: CRNF

CFDA: 12.800
PE #:

Project unit: AERO ENGR Unit code: 22
Project director(s):

PDPI-	LOEWY	R G	AERO ENGR	(404)894-3002
COPDPI-	ATLURI	S N	ENGR COLL	(404)894-2758

Sponsor : AIR FORCE/BOLLING AFB, DC
Division Id: 104 / 3346
Award period: 01-APR-1995 to 31-OCT-1997 (performance) 01-JAN-1998 (reports)

Sponsor amount	New this change	Total to date
Contract value:	0.00	100,000.00
Funded:	0.00	100,000.00
Cost sharing amount:	0.00	0.00

Does subcontracting plan apply?

Title: NONLINEAR AEROELASTIC EFFECTS IN DAMAGED COMPOSITE AEROSPACE STRUCTURES

PROJECT ADMINISTRATIVE DATA

OCA contact: Anita D. Rowland (404) 894-4820

Sponsor technical contact:
DR. SPENCER T. WU
AFOSR/NA
110 DUNCAN AVENUE
SUITE B115

Phone: 2027674988
Fax: BOLLING AFB, DC 20332-0001
Email:

Sponsor issuing office:
JENNIFER L. BELL
AFOSR/PKA
110 DUNCAN AVENUE
SUITE B115

Phone: 2027676836
Fax: BOLLING AFB, DC 20332-0001
Email:

Security class (U,C,S,TS): U
Defense priority rating :

ONR resident rep is ACO (Y/N): N
Supplemental sheet: X

Equipment title vests with: G
NONE ANTICIPATED

Administrative comments -
[redacted]

CA8120 Georgia Institute of Technology Page: 1
Office of Contract Administration 02-DEC-1997 16:58
PROJECT CLOSEOUT - NOTICE

Closeout Notice Date 02-DEC-1997

Project Number E-16-X68 Docs Id [illegible]

Center Number 10/24-6-R8470-0A0

Project Director LOEWY, ROBERT

Project Unit AERO ENGR

Sponsor AIR FORCE/BOLLING AFB, DC

Division Id 3346

Contract Number F49620-95-1-0241

Prime Contract Number

Title NONLINEAR AEROELASTIC EFFECTS IN DAMAGED COMPOSITE [illegible] STRUCTURES

Effective Completion Date 31-OCT-1997 (Performance) [illegible]

Closeout Action:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory and Related Certificate	Y	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

Comments

Distribution Required:

Project Director/Principal Investigator	Y
Research Administrative Network	Y
Accounting	Y
Research Security Department	N
[redacted]	Y
Research Property Team	Y
Supply Services Department/Procurement	Y
Georgia Tech Research Corporation	Y
Project File	Y

DEC 3 1997

NOTE: Final Patent Questionnaire sent to PDPI

J 16-X68 ...

Georgia Tech

Office of Grants and Contracts Accounting

Georgia Institute of Technology
190 Bobby Dodd Way
Atlanta, Georgia 30332-0259
USA
404•894•4624; 2629
Fax: 404•894•5519

August 22, 1995

Office of Naval Research
Ms. Sherry Smallwood
101 Marietta Tower
101 Marietta Street, Suite 2805
Atlanta, GA 30323-0008

Subject: Grant # F49620-95-1-0241

Dear Ms. Smallwood:

Enclosed is the Request for Advance or Reimbursement (SF 270) for the above noted project covering the period April 1, 1995 through July 31, 1995.

If you have any questions or require additional information, please contact Kate Edwards at (404) 894-5522.

Sincerely,

David V. Welch
Director

DVW/ke

Enclosures

c: File E-16-X68/246R84700A0
Wanda Simon, OCA - mailcode 0420

REQUEST FOR ADVANCE OR REIMBURSEMENT

(See instructions on back)

Approved by Office of Management and Budget, No. 80-R0183

PAGE 1 OF 1 PAGES

1. TYPE OF PAYMENT REQUESTED
a. "X" one, or both boxes: ☐ ADVANCE ☒ REIMBURSEMENT
b. "X" the applicable box: ☐ FINAL ☒ PARTIAL

2. BASIS OF REQUEST: ☒ CASH ☐ ACCRUAL

3. FEDERAL SPONSORING AGENCY AND ORGANIZATIONAL ELEMENT TO WHICH THIS REPORT IS SUBMITTED
U. S. AIR FORCE VIA: ONR RR

4. FEDERAL GRANT OR OTHER IDENTIFYING NUMBER ASSIGNED BY FEDERAL AGENCY
F49620-95-1-0241

5. PARTIAL PAYMENT REQUEST NUMBER FOR THIS REQUEST
1

6. EMPLOYER IDENTIFICATION NUMBER
58-0603146

7. RECIPIENT'S ACCOUNT NUMBER OR IDENTIFYING NUMBER
E-16-X68/R84700A0

8. PERIOD COVERED BY THIS REQUEST
FROM (month, day, year): 04/01/95
TO (month, day, year): 07/31/95

9. RECIPIENT ORGANIZATION
Name: GEORGIA TECH RESEARCH CORP.
Number and Street: P. O. BOX 100117
City, State and ZIP Code: ATLANTA, GA 30384

10. PAYEE (Where check is to be sent is different than item 9)
Name:
Number and Street:
City, State and ZIP Code:

11. COMPUTATION OF AMOUNT OF REIMBURSEMENTS/ADVANCES REQUESTED

PROGRAMS/FUNCTIONS/ACTIVITIES ►		(a)	(b)	(c)	TOTAL
a. Total program outlays to date (As of date) 07/31/95		$	$	$	$ 5,980.48
b. *Less:* Cumulative program income					-0-
c. Net program outlays (*Line a minus line b*)					5,980.48
d. Estimated net cash outlays for advance period					-0-
e. Total (*Sum of lines c & d*)					5,980.48
f. Non-Federal share of amount on line e					-0-
g. Federal share of amount on line e					5,980.48
h. Federal payments previously requested					-0-
i. Federal share now requested (*Line g minus line h*)					5,980.48
j. Advances required by month, when requested by Federal grantor agency for use in making prescheduled advances	1st month				
	2nd month				
	3rd month				

12. ALTERNATE COMPUTATION FOR ADVANCES ONLY

a. Estimated Federal cash outlays that will be made during period covered by the advance	$
b. *Less:* Estimated balance of Federal cash on hand as of beginning of advcnce period	
c. Amount requested (*Line a minus line b*)	$

13. CERTIFICATION

	SIGNATURE OF AUTHORIZED CERTIFYING OFFICIAL	DATE REQUEST SUBMITTED
I certify that to the best of my knowledge and belief the data above are correct and		

Home of the 1996 Olympic Village
Georgia Institute of Technology
Office of Grants and Contracts Accounting
Risk Management

August 2, 1996

Office of Naval Research
Mr. Douglas Heaton
101 Marietta Tower
101 Marietta Street, Suite 2805
Atlanta, GA 30303-0008

Subject: Grant # F49620-95-1-0241

Dear Mr. Heaton:

Enclosed is the interim Financial Status Report (SF 269A) for the above noted agreement covering the period April 1, 1995 through March 31, 1996.

If you have any questions or require additional information, please contact Kate Edwards at (404) 894-5522.

Sincerely,

David V. Welch
Director

DVW/ke

Enclosures

xc: File E-16-X68/246R84700A0
Wanda Simon, OCA, mailcode 0420

Office of Grants and Contracts Accounting
190 Bobby Dodd Way
Atlanta, Georgia 30332-0259 U.S.A.
PHONE 404•894•4624 FAX 404•894•5519
RISK MANAGEMENT 404•894•4626

FINANCIAL STATUS REPORT

(SHORT FORM)

(Follow instructions on the back)

1. FEDERAL AGENCY AND ORGANIZATIONAL ELEMENT TO WHICH REPORT IS SUBMITTED	2. FEDERAL GRANT OR OTHER IDENTIFYING NUMBER ASSIGNED BY FEDERAL AGENCY	OMB Approval No.	PAGE	OF
AFOSR	F49620-95-1-0241	0348-0039	1	1 Pages

3. RECIPIENT ORGANIZATION (Name and complete address, including ZIP code)

GEORGIA TECH RESEARCH CORPORATION, P.O. BOX 100117, ATLANTA, GA 30384

4. EMPLOYER IDENTIFICATION NUMBER	5. RECIPIENT ACCOUNT NUMBER OR IDENTIFYING NUMBER	6. FINAL REPORT	7. BASIS
58-0603146	E-16-X68/246R84700A0	☐ YES ☒ NO	☒ CASH ☐ ACCRUAL

8. PROJECT/GRANT PERIOD (See instructions) FROM: (Month, Day, Year)	TO: (Month, Day, Year)	9. PERIOD COVERED BY THIS REPORT FROM: (Month, Day, Year)	TO: (Month, Day, Year)
4/1/95	3/31/97	4/1/95	3/31/96

10. TRANSACTIONS:	I PREVIOUSLY REPORTED	II THIS PERIOD	III CUMULATIVE
a. Total Outlays	0.00	26,375.20	26,375.20
b. Recipient share of outlays	0.00	0.00	0.00
c. Federal share of outlays	0.00	26,375.20	26,375.20
d. Total unliquidated obligations			0.00
e. Recipient share of unliquidated obligations			0.00
f. Federal share of unliquidated obligations			0.00
g. Total Federal share (sum of lines c and f)			26,375.20
h. Total Federal funds authorized for this funding period			100,000.00
i. Unobligated balance of federal funds (Line h minus line g)			73,624.80

11. Indirect Expense

a. Type of Rate (Place "X" in appropriate box) ☒ Provisional ☐ Predetermined ☐ Final ☐ Fixed

b. Rate		c. Base	d. Total Amount	e. Federal Share
FY 1995	40.00%	4,271.77	1,708.71	1,708.71

12. Remarks: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.

FY 1996	43.00%	14,262.05	6,132.67	6,132.67

13. Certification: I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.

Typed or Printed Name and Title	Telephone (Area code, number and extension)
David V. Welch, Director Grants and Contracts Accounting	(404) 894-2629
Signature of Authorized Certifying Official	Date Report Submitted 8/2/96

NSN 7540-01-218-4387 269-201 Standard Form 269A (rev 4-88)

Prescribed by OMB Circulars A-102 and A-110

Questions concerning this report should be directed to Kate Edwards (404) 894-5522.

Home of the 1996 Olympic Village
Georgia Institute of Technology
Office of Grants and Contracts Accounting
Risk Management

N/A

August 12, 1996

Air Force Office of Scientific Research
Ms. Jennifer Bell
AFOSR / PKA
110 Duncan Avenue, Suite B115
Bolling AFB, DC 20332-0001

Subject: Grant No. F49620-95-1-0241

Dear Ms. Bell:

Enclosed is the final Financial Status Report (SF-269A) for the above noted grant for the period April 1, 1995 through March 31, 1996.

If you have any questions or require additional information, please contact Kate Edwards at (404) 894-5522.

Sincerely,

David V. Welch, Director
Grants and Contracts Accounting

DVW/ke

Enclosures

File: E-16-X68/246R84700A0
Wanda Simon, Mailcode 0420

Office of Grants and Contracts Accounting
190 Bobby Dodd Way
Atlanta, Georgia 30332-0259 U.S.A.
PHONE 404•894•4624 FAX 404•894•5519
RISK MANAGEMENT 404•894•4626

FINANCIAL STATUS REPORT

(SHORT FORM)

(Follow instructions on the back)

1. FEDERAL AGENCY AND ORGANIZATIONAL ELEMENT TO WHICH REPORT IS SUBMITTED	2. FEDERAL GRANT OR OTHER IDENTIFYING NUMBER ASSIGNED BY FEDERAL AGENCY	OMB Approval No.	PAGE	OF
AFOSR	F49620-95-1-0241	0348-0039	1	1 Pages

3. RECIPIENT ORGANIZATION (Name and complete address, including ZIP code)
GEORGIA TECH RESEARCH CORPORATION, P.O. BOX 100117, ATLANTA, GA 30384

4. EMPLOYER IDENTIFICATION NUMBER	5. RECIPIENT ACCOUNT NUMBER OR IDENTIFYING NUMBER	6. FINAL REPORT	7. BASIS
58-0603146	E-16-X68/249R84700A0	☐ YES ☒ NO	☒ CASH ☐ ACCRUAL

8. PROJECT/GRANT PERIOD (See instructions) FROM: (Month, Day, Year)	TO: (Month, Day, Year)	9. PERIOD COVERED BY THIS REPORT FROM: (Month, Day, Year)	TO: (Month, Day, Year)
4/1/95	3/31/97	4/1/95	3/31/96

10. TRANSACTIONS:	I PREVIOUSLY REPORTED	II THIS PERIOD	III CUMULATIVE
a. Total Outlays	0.00	26,375.20	26,375.20
b. Recipient share of outlays	0.00	0.00	0.00
c. Federal share of outlays	0.00	26,375.20	26,375.20
d. Total unliquidated obligations			0.00
e. Recipient share of unliquidated obligations			0.00
f. Federal share of unliquidated obligations			0.00
g. Total Federal share (sum of lines c and f)			26,375.20
h. Total Federal funds authorized for this funding period			100,000.00
i. Unobligated balance of federal funds (Line h minus line g)			73,624.80

11. Indirect Expense	a. Type of Rate (Place "X" in appropriate box)			
	☒ Provisional	☐ Predetermined	☐ Final	☐ Fixed
	b. Rate	c. Base	d. Total Amount	e. Federal Share
	FY 1995 40.00%	4,271.77	1,708.71	1,708.71

12. Remarks: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.

FY 1996	43.00%	14,262.05	6,132.67	6,132.67

13. Certification: I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.

Typed or Printed Name and Title	Telephone (Area code, number and extension)
David V. Welch, Director Grants and Contracts Accounting	(404) 894-2629
Signature of Authorized Certifying Official	Date Report Submitted
	8/5/96

NSN 7540-01-218-4387 269-201 Standard Form 269A (rev 4-88)

Prescribed by OMB Circulars A-102 and A-110

Questions concerning this report should be directed to Kate Edwards (404) 894-5522.

E-16-X63
#1
(N2u.)

Robert G. Loewy
Director
School of Aerospace Engineering

Georgia Institute of Technology
Atlanta, Georgia 30332-0150
USA
404•894•3000
Fax: 404•894•2760

September 15, 1995

Dr. Spencer Wu
AFOSR
110 Duncan Avenue
Suite B115
Bolling AFB, DC 20332-0001

Dear Dr. Wu:

This forwards the progress report required under the subject contract. Included is a paper resulting from this research submitted to the AIAA Journal. Please don't hesitate to call, if you have any questions.

Sincerely,

Robert G. Loewy

RGL:kab

Enclosure

cc: Capt. Brian Sanders
Dr. S. Atluri

Progress Report # 1 (Grant No. E16X68)

by

R.G. Loewy & S.N. Atluri

School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

September 15, 1995

1. Status of Effort:

   During the first half of this year, an investigation has been made into the flutter response and aeroelastic stability of microcracked composite plates.

   First, an analytical modeling of moduli reduction due to microcracks was constructed based on a self-consistent method. Several important observations were made as to the effects of microcracking on the overall elastic behavior of the laminates. We next focused on the nonlinear bimodular behavior by investigating two-dimensional flutter responses of microcracked composite plates. Both free vibration and nonlinear flutter responses in supersonic flow were examined using a finite difference and finite element methods. We also performed a linear flutter analysis of a microcracked rotor blade with a single set of reduced moduli in order to demonstrate the roles of reduced elastic couplings in three-dimensional flutter problems. Recently, an effort has been made to develop a complete, three-dimensional modeling of microcracked composite wings. To this end, an aerodynamic model reflecting the latest development in unsteady aerodynamics has been newly constructed. For the structural part, a modal solution method using a first few modes of composite laminate has been implemented. This model is now complete and ready for analysis. Currently, a finite element model is also being formulated.

2. Accomplishments/New Findings:

   The following are summary of new findings:

   (a) Regardless of layer structure and/or stacking sequence, the cracked plates will deform in a bimodular fashion under certain circumstances depending on the crack opening-closure status. Since this bimodular behavior is always coupled with spatial degrees of freedom of deformation, the overall behavior of microcracked composite becomes nonlinear.

   (b) Microcracked composite plates are bound to have different coupling effects than undamaged composite wings. In particular, many of beneficial elastic couplings that are typically used for aeroelastic tailoring may significantly be lost due to the presence of microcracking.

(c) In the case of two-dimensional flutter, the microcracking in composites results in a loss of aeroelastic stability through nonlinear bimodular oscillation as well as by a direct reduction in the bending stiffness. For the case of Graphite/Epoxy $[90/0]_S$ with one 90^o layer microcracked, the reduction in the bending stiffness was as high as 12 %, resulting in approximately 6 % of flutter stability.

(d) Within the framework of linear analysis, decrease in the flutter stability for three-dimensional cases could be attributed to the significant loss in elastic couplings as well as in other stiffness entries, as predicted in the first phase of our research. For this demonstration, a blade model made of Graphite/Epoxy $[\pm 45]_S$ with all microcracks in the lower - 45^o and 45^o plies was examined. It was found that the cracked blade becomes unstable at 2.43 Hz of rotational speed while uncracked blade does not show any instability.

We launched the proposed research on "Nonlinear Aeroelastic Effects in Damaged Composite Aerospace Structures" by first investigating the effects of microcracks on aeroelastic behavior of composite plates. Microcracking is one of the two types of damage that we proposed to study in our original proposal. We believe that our work during the past half year represents the first effort to formulate the microcracked composite structure undergoing aeroelastic oscillations. The results summarized above agree well with our physical reasoning, and the problems that we defined deserve to be investigated further using fuller analyses. As indicated in our proposal, the importance of microcrack damage in composite laminates lies in its role as a modulus changer rather than as a strength changer. It was shown that this modulus change can significantly alter the aeroelastic stability envelop even at a low level of crack density. Since modern aircraft are making use of composite materials for the purpose of aeroelastic tailoring as well as enhancing strengths, it goes without saying that the microcracks will have definite effects on the overall structural integrity and safety of aircraft. This would be truer of military aircraft which, due to their special needs under unusual flight conditions, require higher degrees of safety margins.

3. Personnel Supported:

   - Dr. Satya N. Atluri, Professor
   - Dr. Robert G. Loewy, Professor
   - Dr. Taehyoun Kim, PostDoctoral Fellow

4. Publications:

   Kim, T., Atluri, S.N., and Loewy, R.G., "Modeling of Microcrack Damaged Composite Plates Undergoing Nonlinear Bimodular Flutter Oscillations", submitted to AIAA Journal in June, 1995.

5. Interactions/Transitions:

   (a) Participation/presentations: Kim, T., Atluri, S.N., and Loewy, R.G., "Modeling of Microcrack damaged Composite Plates Undergoing Nonlinear Bimodular Flutter Oscillations", presented by Dr. T. Kim at the Third U.S. National Congress on Computational Mechanics, Dallas, TX, June 12-14, 1995.

   (b) Consultative and advisory functions to other laboratories and agencies: None

   (c) Transitions: None

6. New discoveries, inventions, or patent disclosures: None

7. Honors/Awards: None

3. Personnel Supported:
   - Dr. Satya N. Atluri, Professor
   - Dr. Robert G. Loewy, Professor
   - Dr. Taehyoun Kim, PostDoctoral Fellow

4. Publications:

   Kim, T., Atluri, S.N., and Loewy, R.G., "Modeling of Microcrack Damaged Composite Plates Undergoing Nonlinear Bimodular Flutter Oscillations", submitted to AIAA Journal in June, 1995.

5. Interactions/Transitions:
   (a) Participation/presentations: Kim, T., Atluri, S.N., and Loewy, R.G., "Modeling of Microcrack damaged Composite Plates Undergoing Nonlinear Bimodular Flutter Oscillations", presented by Dr. T. Kim at the Third U.S. National Congress on Computational Mechanics, Dallas, TX, June 12-14, 1995.
   (b) Consultative and advisory functions to other laboratories and agencies: None
   (c) Transitions: None

6. New discoveries, inventions, or patent disclosures: None

7. Honors/Awards: None

E-16 X68
#2

NONLINEAR AEROELASTIC EFFECTS IN DAMAGED COMPOSITE AEROSPACE STRUCTURES

Grant F49620-95-1-0241

Report # 2.

Drs. R.G. Loewy, S Atluri, and O.A. Bauchau.
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia, 30332.

September 2, 1996

1 Objectives

Although aerospace vehicle structures are being designed making greater use of advanced filamentary composite materials than ever before, virtually all the composite in current use are designed to carry the major loads in the fiber. That is matrix material is left largely unloaded. Just how little load appears in the matrix material depends, of course, on the moduli of fibers and matrices; matrix materials carry very little load in graphite/epoxy composites, but a little more in glass/epoxy laminates.

Nevertheless, the integrity of the matrix material plays important structural roles beyond the fundamental ones of transfering tensile loads around imperfections or damage in an individual fiber reinforcement and shear transfer from one ply to another. Matrix constraint of fiber deflection in transverse directions is a key factor in preventing buckling of plies under compressive loads. Such local instabilities are, of course, a principal adverse consequence of delamination.

Further, composites designed and used so as to have no major loads in the matrix material can not provide elastic couplings, and there is a widespread agreement that elastic copuplings (e.g. bending/torsion or extension/torsion) can have substantial benefits. Examples include stabilizing the static aeroelastic divergence of forward swept wings and eliminating dynamic instabilities encountered by advanced helicopter rotor blades. Elastic couplings, in general, require *loading* the matrix material in composite laminates.

There is, therefore, strong justification for considering the behavior of aerospace structures in the presence of likely and, certainly, unavoidable damage in matrix materials. The purpose of the research proposed here is to study the aeroelastic behavior of composite aircraft and missile wings in the presence of two kinds of damage in the matrix material. The first kind is the likely sub-surface delamination that can occur, for example, when a tool is dropped on the upper surface and repeated upward bending moments cause growth of the delaminated region. The second is the micro-cracking which inevitably exists in both resin matrix and metal matrix composites. Delamination sufficient to cause ply buckling under compressive loads, say, in only an upper surface will cause a nonlinear load-deflection relationship in bending. While micro-cracking of the matrix has negligible effect on the overall elastic properties of composite structures now in service because these composites are designed so that matrix materials are substantially unloaded, their effect on the aeroelastic moduli of structures *tailored* to provide elastic couplings can be substantial. Micro-cracking distribution can cause nonlinear load-deflection characteristics in bending, too.

2 Status of Effort

In the previous reporting period, the investigation has focused on the aeroelastic analysis of structures with micro-cracked laminates. The reduced stiffness of the micro-cracked laminate was evaluated using the self consistent model developed by Laws, Dvorak, and Hejazi. The crack opening/closure criterion is based on the sign of the strain normal to the fiber direction accomodated by the cracks. The presence of micro-cracks in laminates were shown to lead to bimodular vibration of composite plates.

A one dimensional, panel flutter investigation has shown that micro-craks in composites result in the loss of aeroelastic stability through direct reduction in stiffness and nonlinear bimodular oscillations. Typical results of this analysis were reported in the publication given below.

3 Accomplishments/New Findings

In the present reporting period, the investigation has turned to realistic configurations involving aircraft wings presenting elastic couplings. In such structures, the strength of the elastic coupling, a central parameter for the design of aeroelastically tailored wings, strongly depends on the matrix material properties which in turns are strongly affected by matrix micro-cracking. To ensure the realism of the analysis, the lay-ups used for the X-29 forward swept wing fighter were used as a base line. The bending, torsional, and coupling stiffnesses of the wing were evaluated for the nominal value of the material properties and for those corresponding a matrix saturated by micro-cracks. The effect of nonlinear shear stress/strain material behavior was also investigated, as suggested at AFOSR workshop last June. Though such effect can conceptually be as significant as that of micro-craks, the level of shearing stress present in this design was low, and as a result, linear properties were an excellent approximation.

The bending and torsional stiffnesses of the wing were slightly degraded in the presence of micro-craks (typically, a 5% decrease in stiffness was observed), whereas dramatic changes in the coupling stiffness were observed (up to 150%). This change in coupling stiffness will dramatically affect the static divergence speed of the wing which the elastic coupling is meant to increase, and will also affect the flutter speed of this forward swept wing. This flutter analysis is presently being conducted.

4 Personel Supported

The following personel has been supported under this grant:

1. Dr. Satya N. Atluri, professor;
2. Dr. Robert G. Loewy, professor;
3. Dr. Taehyoun Kim, post-doctoral fellow;
4. Mr. Haochuan Zhang, graduate research assistant;

5 Publications

Kim, T., Atluri, S.N., Loewy, R.G. " Modeling of Micro-crack Damaged Composite Plates Undergoing Nonlinear Bimodular Flutter Oscillations". Accepted for publication in AIAA Journal.

6 Interactions/Transitions

1. A summary of this work was presented at the AFOSR workshop in Virginia Beach, Virginia.
2. An abstract was accepted for presentation of this work at the "Nonlinear Dynamical Systems Symposium" to be held January 6-9, 1997 in Reno, NV.

7 New Discoveries, Inventions, Patent Disclosures

None.

8 Honors and Awards

None.

E-16-X68
#3

Nonlinear Aeroelastic Effects in Damaged Composite Aerospace Structures.

AFOSR Grant #F49620-95-1-0241, Major Brian Sanders, contract monitor.

O. A. Bauchau and R.G. Loewy.

Georgia Institute of Technology.

School of Aerospace Engineering,

Atlanta, Georgia, 30332-0150.

November 20, 1997

Research Objectives

Although aerospace vehicle structures are being designed making greater use of advanced filamentary composite materials than ever before, virtually all the composites in current use are designed to carry the major loads in the fibers. That is, matrix material is left largely unloaded. Nevertheless, the integrity of the matrix material plays important structural roles beyond the fundamental ones of transferring tensile loads around imperfections or damage in an individual fiber reinforcement and shear stresses from one ply to another. Matrix constraint of fiber deflection in transverse directions is a key factor in preventing buckling of plies under compressive loads. Such local instabilities are, of course, a principal adverse consequence of delamination.

Composites designed and used so as to have no major loads in the matrix material can not provide elastic couplings, and there is a widespread agreement that elastic couplings (e.g. bending/torsion or extension/torsion) can have substantial benefits [1]. Examples include stabilizing the static aeroelastic divergence of forward swept wings and eliminating dynamic instabilities encountered by advanced helicopter rotor blades. Elastic couplings, in general, require loading the matrix material in composite laminates.

The first part of this research investigated the nonlinear aeroelastic behavior of wing structures in the presence of likely and certain unavoidable damage in matrix materials. The investigation focused on matrix micro-cracking which inevitably exists in both resin matrix and metal matrix composites. While micro-cracking of the matrix has a modest effect on the overall elastic properties of composite structures now in service because these composites are designed so that matrix materials are substantially unloaded, their effect on the aeroelastic behavior of structures tailored to provide elastic couplings can be substantial. Micro-cracking was shown [2] to give rise to limit cycle oscillations in nonlinear bi-modular flutter of damaged composite panel.

From an operational standpoint, routine inspection will only detect the most serious damage types, and maintenance programs involving complete structural inspections only take place after many flight hours. As a result, deterioration of aeroelastic properties can go undetected for extended periods of time, and aircrafts flying in such conditions could have significantly reduced stability boundaries.

Both micro-cracking and delamination are damage processes that can lead to nonlinear material behavior and possible nonlinear aeroelastic phenomena. A fundamental difference exists between these two damage mechanisms. Micro-cracking is an unavoidable phenomenon associated with curing stresses and the repeated application of service loads. After a some time in service, a "shake-down" state is reached where significant micro-cracking is present throughout the structure. On the other hand, delamination is a localized phenomenon resulting from foreign object damage, manufacturing defects, or the coalescence of extensive micro-cracking. Delaminations can appear between the layers of a laminate, and under specific loading conditions, these delaminations can grow. Though the size of the delamination can become large when compared to ply or laminate thickness, it is unlikely that this damage will become large when compared to the size of the overall structure without being detected by routine structural inspection. As a result, studying the aeroelastic behavior of wings with delaminations extending over half the span, for instance, would be an academic exercise. On the other hand, the aeroelastic behavior of wings with significant, but localized delaminations is unlikely to be different from that of undamaged wings because a localized delamination only results in a very small change in overall wing stiffness.

There are cases, however, where delaminations can occur over large portions of structural components such as control surfaces, for instance. A given size delamination initiated by foreign object impact could be fairly small compared to wing size, but rather large with respect to aileron or rudder size. Furthermore, the rather high stiffness of actuators, placed so as to be close to the surface being driven, makes for relatively high frequency control surface rotation characteristics. Finally, control surfaces being lighter gage structures are often designed by stiffness rather strength criteria, and the damage caused by an impact of given energy level is likely to result in a more dramatic stiffness reduction for such components. As a result, the second part of this research was devoted to the study of the aeroelastic behavior of wing-aileron structures in the presence of delamination damage.

Reseach Findings

Matrix micro-cracking of composite laminates was found to have a modest effect on the sectional stiffnesses of wings, and on the resulting aeroelastic behavior, though the effect can be very significant on elastic coupling terms. A complicating effect of matrix micro-cracking is that it gives rise to nonlinear material constitutive laws in the presence of nonuniformly distributed crack densities. In particular, nonlinear, bi-modular sectional stiffness properties are likely to occur in practical situations.

Matrix damage does not seem to have a significant influence on the flutter speed. But for the aeroelastic response to a sharp edged gust, a clear qualitative difference exists between the aeroelastic reponses of the undamaged and damaged wings. The undamaged wing exhibits strong aerodynamic damping characteristics, whereas large amplitude, undamped aeroelastic oscillations, typical of a limit cycle behavior, were observed for the damaged case. At speeds close to, but lower than the flutter speed the peak-to-peak amplitudes for the associated oscillatory root shear force and bending moment are predicted to be as much as an order of magnitude larger for the damaged wing as compared to the undamaged wing. This limit cycle behavior seems to disappear at lower air speeds.

Using a three-dimensional aerodynamic and structural model to simulate wing-aileron flutter when localized delaminations are present, it has been found that the flutter speed of the damaged structure is approximately the same as that of the undamaged structure. But, for a significant range of speed below flutter, high-amplitude oscillations are observed, typical of a limit cycle behavior. These oscillations induce high-amplitude, cyclic stresses in the aileron and at the wing root, that could significantly reduce the fatigue life of the entire structure.

References

[1] Ehlers, S.M. and Weisshaar, T.A., "Adaptive Wing Flexural Axis Control." *Proceedings of the Third International Conference on Adaptive Structures*, San Diego, CA, Nov 9-11, 1992, pp 28-40.

[2] Kim T. Atluri S.N., and Loewy R.G., "Modeling of Micro-Crack Damaged Composite Plates Undergoing Nonlinear Bi-Modular Flutter." *AIAA Journal*, To appear.